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Novel Dosimeter Using a Nontoxic Phosphor for Real-Time Monitoring of Patient Radiation Dose in Interventional Radiology

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OBJECTIVE. To our knowledge, no feasible method exists for real-time measurement of the radiation dose given to the patient during interventional radiology (IR) procedures. Therefore, we produced a prototype of a real-time dosimeter for patients undergoing IR that uses a nontoxic phosphor. The basic characteristics of the real-time dosimeter prototype are comparable to those of the previously used skin dose monitor, with the exception that our prototype has the distinct advantage of including multichannel sensors.

CONCLUSION. The novel real-time dosimeter system is expected to be useful for measuring patient exposure to the radiation dose during IR procedures.

Keywords: fluoroscopy, interventional radiology, patient skin dosimeter, radiation protection, real-time dose measurement

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Radiation-induced injuries have been reported in patients after interventional radiology (IR) procedures [1–5]. Therefore, real-time monitoring of individual radiation doses is important to avoid such injuries [6–10]. To our knowledge, there currently is no feasible real-time dosimeter available for IR. Although the skin dose monitor (model 104-101, McMahon Medical) was previously used for real-time monitoring of radiation dose exposure, it was discontinued because it contained zinc-cadmium phosphor, which is a toxic substance [11]. Therefore, we developed a novel real-time dosimeter that uses a nontoxic sensor for patients undergoing IR. The purpose of this study was to evaluate the fundamental characteristics of this novel real-time dosimeter. We also assessed the feasibility of our novel device for real-time measurement of radiation doses given to patients during IR procedures.

Materials and Methods

Development of a Real-Time Dosimeter for Interventional Radiology

We developed a novel real-time dosimeter for IR that uses a nontoxic sensor. The device consists of photoluminescence sensors (a maximum of four nontoxic phosphor sensors), an optical fiber cable, a photodiode, and a digital display that includes the power supply (Fig. 1). The dosimeter can be powered by a dry-cell battery or AC power. The photodiode is suitable for measuring red light. Our previous research showed that Y_2O_2S:Eu,Sm is a suitable red light–emitting phosphor because it is nontoxic, exhibits relatively high sensitivity, and is subject to almost no deterioration in brightness [12].

Basic Performance (Energy, Dose, and Dose-Rate Dependence) of the Novel Real-Time Dosimeter

A diagnostic x-ray system with a high-frequency inverter generator (UD-150, Shimadzu) was used to evaluate the basic performance of the new real-time dosimeter. For comparison, we also evaluated the capabilities of the skin dose monitor under the same conditions.

Dose measurements (measured in air Kerma) were compared with measurements obtained using a calibrated (i.e., traceable from the national reference exposure dose) thimble-type 6-mL ion chamber (model 9015 dosimeter, Radcal). Irradiation of the sensor and reference ion chamber was performed in air under identical x-ray irradiation conditions, with the use of a novel dosimeter measurement (i.e., a measurement of energy dependence, with a tube voltage of 60–120 kV, a tube current of 250 mA, and an exposure time of 0.4 second). An average value was derived from three measurements.

The energy (tube voltage) dependence of the dosimeters was measured at 60, 70, 80, 90, 100, 110, and 120 kV (tube current, 250 mA; exposure time, 0.4 second). Dose linearity was 0.19–590 mGy (tube voltage, 80 kV). The dose-rate dependence of the dosimeters was also measured for eight dose rates that ranged from 0.7 to 40 mGy/s (tube voltage, 80 kV). The batch uniformity of each of the four sensors of the novel dosimeter was evaluated under identical x-ray irradiation conditions (tube voltage, 80 kV; tube current, 250 mA; exposure time, 0.4 seconds).

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Angular Dependence of the Novel Real-Time Dosimeter

A digital cine x-ray system was used for measurements of angular dependence. For all measurements, the sensor was placed in the isocenter of the x-ray system (at a distance of 75 cm from the tube focus) and irradiated in free air. The dependence of the sensor on the x-ray beam angle in air was measured at 0°, ± 10°, ± 20°, ± 30°, ± 40°, ± 50°, ± 60°, ± 70°, ± 80°, and 90° along the vertical (long) and horizontal (short) axes of the sensor under the same x-ray irradiation conditions (tube voltage, 80 kV; tube current, 50 mA; exposure time, 5 milliseconds), with the measurement at 0° used as the reference value. We also evaluated measurements of the angular dependence of the skin dose monitor under the same conditions.

Fluoroscopic Image of the Sensor and Cable of the Novel Real-Time Dosimeter

A digital cine x-ray system with a flat-panel detector was used to obtain a fluoroscopic image of a sensor placed on a chest phantom. The skin dose monitor was also tested under these conditions.

Results

Basic Performance

The novel real-time dosimeter had low energy dependence, similar to findings for the skin dose monitor (Fig. 2). Both the novel dosimeter and the skin dose monitor exhibited excellent dose linearity (i.e., dose dependence) ($R^2 = 1.00$) (Fig. 3).

Dose-rate dependence is shown in Figure 4. The dose-rate dependence values for the two dosimeter systems were within 5% of each other. However, at very low dose-rates, the dose-rate dependence of the novel dosimeter was better than that of the skin dose monitor. Values for the batch sensitivity uniformity (presented as the SD divided by mean) of the four sensors of the novel dosimeter were within 10%.

Angular Dependence

Figure 5 shows the angular dependence of the real-time dosimeter sensor along the horizontal (i.e., short) axis of the sensor. Angular dependence along the vertical (long) axis was similar to that along the horizontal (short) axis (figure not shown). Our novel real-time dosimeter had a similar or somewhat inferior angular response, when compared with the angular response of the skin dose monitor. For example, the novel real-time dosimeter exhibited a reliable dose response of 0° ± 50° in the horizontal direction, and sensitivity exceeded 80% over the same range.

TABLE 1: Characteristics of Phosphors Used for the Skin Dose Monitor and Novel Dosimeter

Characteristic	Skin Dose Monitor	Novel Dosimeter
Mechanism of action	Red phosphor–based photoluminescence	Red phosphor–based photoluminescence
Chemical stability	Stable, toxic	Stable, nontoxic
Heat and radiation resistance	Stable	Stable
Linearity and dose-rate dependence	Good	Good
Energy and tube voltage dependence	Marginal energy dependence	Marginal energy dependence

Fluoroscopic Image

Figure 6 shows a fluoroscopic image of a sensor and cable placed on a chest phantom (tube voltage, 80 kV). The cable of the new dosimeter was invisible on the fluoroscopic images, as was the cable of the skin dose monitor. Although the sensor of the novel dosimeter is slightly more noticeable than the sensor of the skin dose monitor, we do not think that it would cause any inconvenience during IR procedures.

Discussion

During IR procedures, patients can be injured as a result of prolonged exposure to x-ray radiation. To protect against such injury, monitoring the radiation dose in real time is required. If exposure is monitored in real time, the IR procedure can be interrupted if the radiation dose to which the patient is exposed exceeds the threshold dose for radiation injury. In other words, real-time monitoring of the maximum radiation skin dose to which a patient is exposed is essential for the safety and effectiveness of IR.

Furthermore, if more than one effective working view is available, a combination of views from different angles and real-time monitoring of the radiation skin dose to which the patient is exposed can prevent a given area of the skin from receiving excessive radiation, thereby reducing the risk of radiation injury. However, to our knowledge, there currently is no device that can directly measure radiation doses in real time, because the skin dose monitor is no longer produced because of the toxicity of its zinc-cadmium sensor. Table 1 summarizes the characteristics of the phosphors associated with the skin dose monitor and the novel dosimeter.

Some new technologies are able to provide real-time monitoring but are not suitable for patients undergoing IR for various reasons. For example, the patient skin dosimeter (PSD, Unfors Instruments) can accurately measure radiation doses to the skin in real time. However, because the sensor and cable of the patient skin dosimeter are clearly visible on fluoroscopic images, the IR procedure is severely impeded [13]. In addition, another real-time dosimeter (RaySafe i2 system, Unfors Instruments) has also been introduced, but this dosimeter is designed to measure occupational exposure. It is not to be used as a real-time dosimeter for patients undergoing IR [14]. Because the aforementioned technologies are not suitable for patients undergoing IR, newer technologies that can enable real-time monitoring of the radiation doses received by such patients are needed.

We developed a novel real-time patient dosimeter for use in IR procedures. This novel device consists of a photoluminescence sensor (a Y_2O_2S:Eu,Sm phosphor, which is a nontoxic substance) and is equipped with an optical fiber, photodiode, and display. We previously showed that Y_2O_2S:Eu,Sm is a nontoxic red light–emitting phosphor that can be used instead of zinc-cadmium phosphor, which is a toxic substance. A red light–emitting phosphor is necessary because photodiodes can detect red light efficiently. Because photodiodes are small, they are suitable for use in a multichannel real-time dosimeter.

Our basic performance results for the novel dosimeter (including measurements of energy dependence and linearity) indicated that its performance was equivalent to that of the skin dose monitor. In future studies, however, a phosphor with greater sensitivity may be required to measure particularly low dose rates.

Like the skin dose monitor, the cable of the novel dosimeter is not radiopaque on fluoroscopic images. However, the sensor of the novel dosimeter is comparatively more visible on a fluoroscopic image than is the sensor of the skin dose monitor. Given that the sensor diameter is quite small, we predict that the sensor of the novel dosimeter would cause only minimal inconvenience during IR procedures. In addition, the fact that the sensor is somewhat radiopaque might be an advantage

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because the location of the point used to measure the patient dose is thus clear.

The novel real-time dosimeter can be equipped with multichannel sensors (a maximum of four sensors), whereas the skin dose monitor had only a single sensor. The multichannel sensors are one of the major advantages of the novel dosimeter because real-time dose measurements are available from four sensors simultaneously, thereby enabling accurate detection of the maximum radiation skin dose. The sensor must be placed in the field in which x-ray exposure is maximal to evaluate the maximum radiation skin dose; therefore, predicting the maximum radiation skin dose site before the IR procedure commences is necessary. Evaluating the maximum radiation skin dose with only a single sensor is problematic. Thus, the novel dosimeter is an effective tool for real-time measurement of the dose to the patient during IR procedures.

Future studies will evaluate the usefulness of the novel dosimeter in IR procedures performed in clinical settings. For example, a validation study of the novel dosimeter will be required to investigate high dose rates during IR procedures.

In summary, we produced a prototype of a novel real-time dosimeter that uses nontoxic phosphor for patients undergoing IR. The basic characteristics of the novel dosimeter are comparable to those of the previously used skin dose monitor, although our dosimeter benefits from having (up to four) multichannel sensors. Therefore, we suggest that our novel dosimeter is superior to the skin dose monitor for measuring the dose of radiation exposure to the skin during IR procedures.

Limitations

The novel real-time dosimeter has some energy dependence, similar to that of the skin dose monitor. To accurately evaluate the radiation dose to the patient, correction of energy dependence may be required.

Our novel dosimeter exhibits a low degree of angular dependence. For angles larger than 50°, correction of angle dependence is necessary.

In conclusion, we developed a novel real-time patient skin dosimeter that uses a nontoxic phosphor. The performance of our novel dosimeter was equivalent to that of the skin dose monitor with respect to energy dependence and linearity, among other parameters. To our knowledge, no feasible method currently exists for real-time measurement of the radiation dose to which the patient is exposed during IR procedures. Therefore, the novel real-time dosimeter system is expected to be useful for measuring the radiation exposure dose given to patients undergoing IR procedures.

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(Figures start on next page)

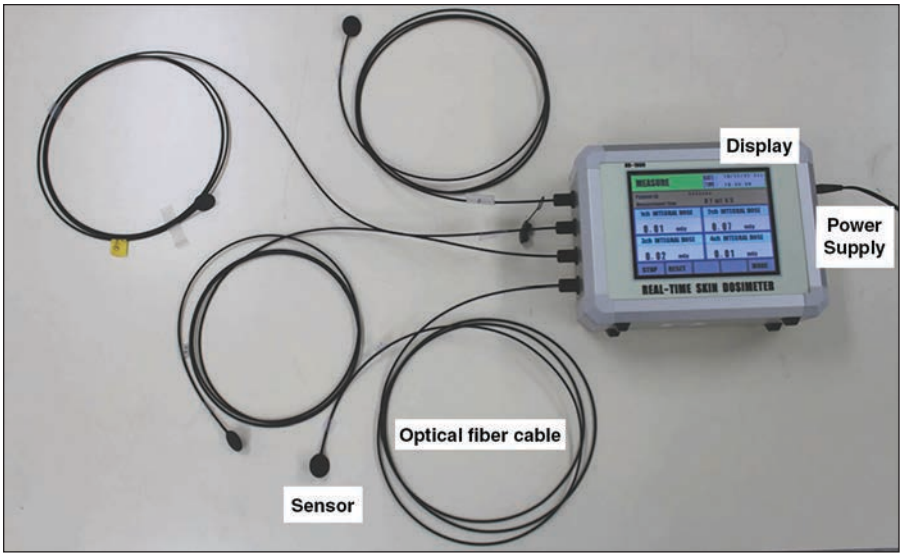

Fig. 1—Photograph of novel patient radiation dosimeter. Dosimeter with multichannel sensors allows real-time dose measurements to be obtained from as many as four sensors simultaneously.

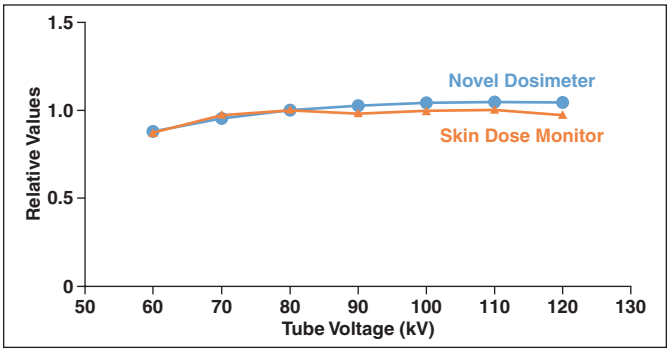

Fig. 2—Energy dependence of two real-time dosimeters: novel dosimeter and skin dose monitor. Relative values are real-time dosimeter measurements divided by ion chamber measurement normalized at 80 kV.

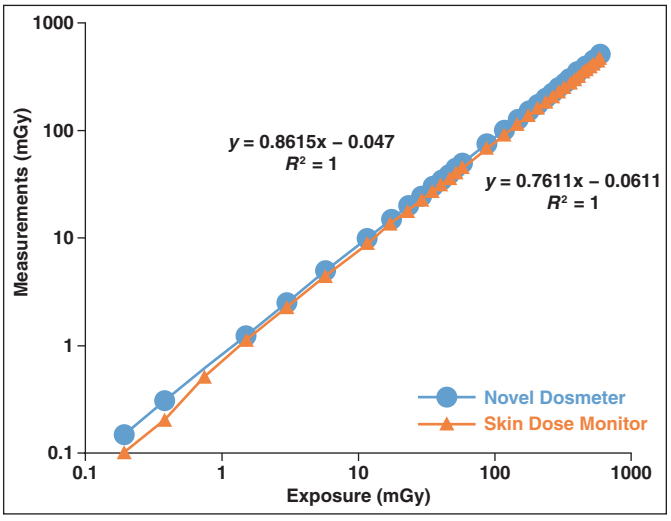

Fig. 3—Linearity (dose-dependence) measurements of real-time dosimeters (novel dosimeter and skin dose monitor). Exposure value is ion chamber measurement.

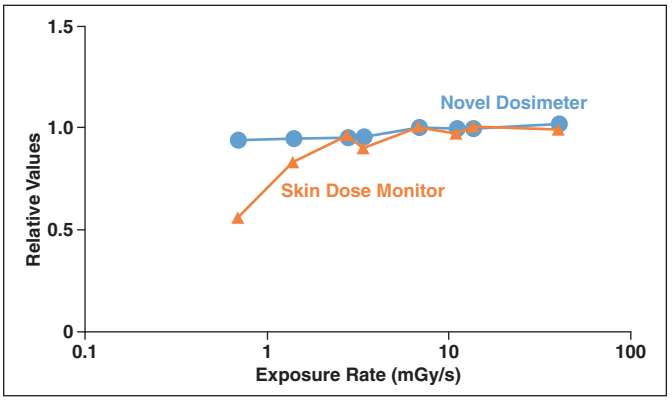

Fig. 4—Dose-rate dependence of real-time dosimeters (novel dosimeter and skin dose monitor). Relative values were real-time novel dosimeter and skin dose monitor measurements divided by exposure rate (i.e., ion chamber measurement). Relative values were normalized at 7 mGy/s.

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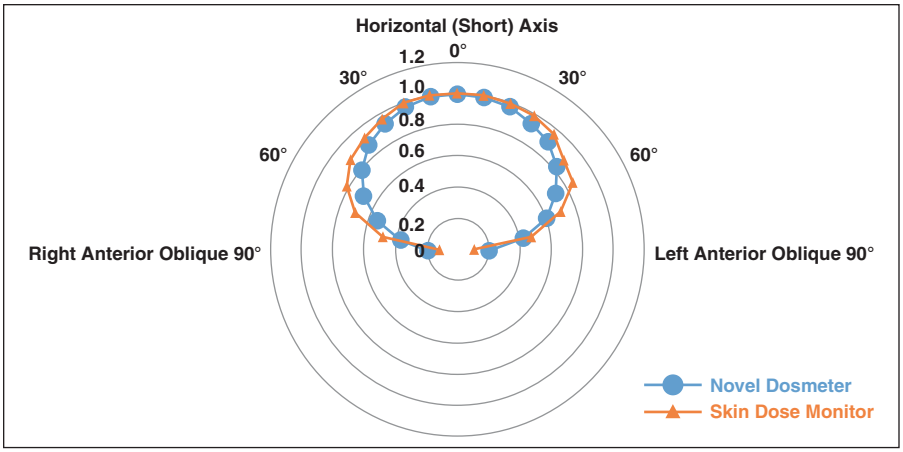

Fig. 5—Angular dependence of real-time dosimeters (novel dosimeter and skin dose monitor) with respect to horizontal (short) axis. Angular dependence along the vertical (long) axis was similar to that along the horizontal (short) axis (data not shown).

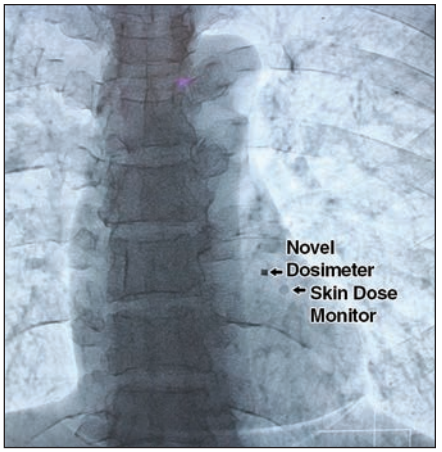

Fig. 6—Fluoroscopic image of sensors placed on chest phantom (tube voltage, 80 kV). Optical fiber cables of both novel dosimeter and skin dose monitor were invisible. Sensor of novel dosimeter was more radiopaque than that of skin dose monitor; however, sensor of novel dosimeter was small and thus would not impede interventional radiology procedure.

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